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Final Report on:

Study of Organized Structures in the Post-Stall Flow Over Wings

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Research Team: Steven Yon, Ph. D. Student SDSU
Joseph Katz, Principal Investigator, SDSU
James Ross, Principal Investigator, NASA Ames.

Summary:

This study of the separated flow over unswept wings is a result of the cooperation between SDSU and NASA Ames Research Center. The research had elements of wind-tunnel and numerical experimentations which were carried out both at SDSU and at Ames research center. One of the important accomplishments of this study is the measurement of the time-dependent pressures on a stalled airfoil. The three-dimensional, cellular nature of the separation pattern on the wing was documented and the dominant frequencies of the pressure flactuations were recorded. The lateral instability of this cellular pattern was observed first but this phenomenon seemed to be arbitrary and not periodic. The existence of a frequency, lower than the anticipated wake shedding frequency, was documented (which was reported only once before in the open literature). This finding may prove valuable for the noise reduction efforts of the high-lift systems of landing aircraft.

Extensive numerical investigations with the INS2D code indicated that the existence of the above mentioned low-frequency oscillations can be captured by the computations. Prediction of the flow separation point at a given angle of attack is still difficult, but the trends are close to the experimental observations. For example, the onset of stall is similar in both cases, but in the computations the events were delayed to somewhat higher angles of attack. Past experience indicate that this discrepancy can be cured by increasing grid density in the vicinity of the separation point, by using certain forms of adaptive grids.

This research effort resulted so far in one joint publication (Ref. 5) and two more papers were completed and submitted for publication. (All three articles are enclosed with this document.) The following paragraphs provide a short overview of the technical results of this project and more details can be found in the enclosed articles.

Introduction:

The unsteady aerodynamics of separated high angle of attack flows over rectangular wings have significant implications for the high angle of attack performance and stability of military, commercial, and general aviation aircraft. Experimental and numerical investigations of the airfoil shapes used on these airplanes are primarily carried out under the assumption that the resulting flow field is two dimensional. This assumption is called into question by the three dimensional structures noted in the surface flow visualization experiments of Winkelmann and Barlow (1980) and Gregory et al. (1970). These structures, termed stall cells by Winkelmann, are observed in a narrow angle of attack range beginning just after the point of maximum lift and are interpreted to be the surface manifestation of discrete regions of separated flow bounded laterally by narrow regions of attached flow. Stall cells occur quasi periodically along the span of the upper surface of an incipiently stalled rectangular wing, the number of cells being determined by aspect ratio. In the same angle of attack range over which stall cells are observed, Zaman et al. (1989) and Bragg and Zaman (1995) have noted upper surface velocity fluctuations in the separated region corresponding to large amplitude motions of the leading edge separated shear layer. These fluctuations occur with a Strouhal number well below the values of 0.15-0.2 commonly thought to characterize unsteady wakes behind bluff bodies. Instead, the shear layer fluctuations occur at approximately the frequencies characteristic of stall flutter as noted by Armstrong and Stevenson (1960) and Baker (1955) and have been hypothesized to be the driving force for that phenomena. To date, no connection has been made between stall cells and the low frequency fluctuations. The present study attempts to investigate, through wind tunnel experimentation and computational simulation, the origins of stall cell separation and low frequency wake fluctuations and their relationship and to apply the increased understanding of unsteady separated flows toward safety and performance enhancing modifications to wing design.

Method:

Wind tunnel investigation of the separated flow phenomenon indicated above took place in the SDSU low speed wind tunnel. This facility is a closed cycle, vertical return tunnel with a 3'x4' test section and a maximum speed of 180 mph. For the current test, tunnel speed is set to 140 mph, which corresponds to Re=620,000 with the 6 inch chord model. The wing model employs six unit aspect ratio sections with NACA 0015 profile which can be combined to produce finite wings with aspect ratio variable in integer increments from 2 to 6. All six sections are tufted for surface flow visualization. One of the sections is fitted with a chordwise array of five high frequency Endevco pressure transducers to record unsteady static pressures and five static pressure taps for mean static pressure measurement. The spanwise placement of the instrumented section is variable in order to allow examination of various parts of the surface flow field as indicated by the surface flow patterns.

Numerical simulation of the separated flow phenomenon is provided by time accurate solution of the unsteady Navier Stokes equations. Proper simulation of the fully three dimensional aspects of unsteady separation would require impractical computer memory and CPU resource allocations. Instead, we employ a two dimensional model to investigate the shear layer instabilities hypothesized to account for the low frequency velocity fluctuations. The NASA Ames developed code INS2D is employed with a Baldwin-Barth one equation turbulence model. Consistent with previous two dimensional numerical simulations (Zaman et al., 1989), turbulence production in the boundary layer is assumed to begin at the leading edge stagnation point.

Results:

Flow visualization with the NACA 0015 finite wing models indicates that discrete stall cells exist in the upper surface flow field of finite wings with aspect ratios greater than 3. The optimal angle of attack for stall cell separation on the current model is around 17 degrees, which is slightly less than that found by Winkelmann (1980) with a Clark Y section of comparable thickness. The stall cells are dynamic and move laterally along the span of the model, a phenomena not observed before. Varying the aspect ratio results in stable stall cell patterns when the aspect ratio is approximately divisible by 3. For aspect ratios between these stable points, the separation pattern is unstable and switches between the two adjacent stable patterns.

Mean static pressure within the stall cell is essentially constant over the model chord, but within the attached regions bounding the individual cells, the mean pressure distribution strongly resembles that of an attached flow with angle of attack significantly less than the model orientation.

Time varying pressures within the stall cells indicate the presence of large amplitude low frequency components similar to those observed by Zaman et al. (1989) and Bragg and Zaman (1994). These fluctuations are strong in the vicinity of the model and much weaker in the wake. Analysis of the time series shows that the pressure fluctuations convect streamwise with a speed approximately half the free stream speed. Significant time periods during which no large pressure fluctuations are observed indicates that there is no causal connection between the low frequency fluctuations and the occurrence of stall cells. Additional observations indicate that the low frequency fluctuations are not related to a periodic stall/un-stall of the upper surface as reported by Zaman et al. (1989) and Moss (1979). Increasing the angle of attack past the range of stall cell stability results in greatly decreasing the magnitude of the model surface pressure fluctuations. Wake pressure fluctuations, however, increase in magnitude with increasing angle of attack and occur with frequencies which are consistent with a von Karman vortex street structure in the wake.

The computational simulation begins with the impulsive acceleration of the 2-D section at the required angle of attack. The resulting load histories indicate the presence of three distinct regimes, first reported by Katz et al. (1994) in a laminar simulation. Transient effects include such phenomena as delay of the Kutta condition, potential lift buildup, and possible trapped vortex formation (depending on angle of attack) which may explain the high lift observed on numerous unsteady flows. After the passage of the transient events ($tV_{\infty} / c > 15$), the load histories contain periodicities which may model the pressure fluctuations observed in the wind tunnel experiments. At very high angles of attack, these fluctuations occur with Strouhal numbers in the range 0.15 - 0.20, consistent with a von Karman vortex street wake. At slightly lower angles of attack, the dominant lift fluctuations occur at frequencies corresponding to Strouhal numbers near 0.1, or approximately half the expected bluff body value. The existence of this second excitation frequency is important to the study of airframe noise at high lift conditions.

Conclusions:

1) Stall cell separation is a dynamic phenomena. Individual stall cells exhibit considerable lateral movement.
2) Low frequency pressure fluctuations are confined to the vicinity of the model and are distinct from the higher angle of attack von Karman vortex street structures observed in the wake.
3) Low frequency surface pressure fluctuations are not causally related to stall cell separation and are probably not indicative of a periodic stall/un-stall cycle.

Additional details of the experimental and computational work are provided in the attached papers which are an integral part of this report.

References:

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